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Citation for published version:
Mignard, D 2016, 'Bringing the magic of light to remote areas where resources are scarce: Beautiful demonstrations of interference patterns using laser pens and fibres', *Physics Education*, vol. 51, no. 5, pp. 054002-054009. https://doi.org/10.1088/0031-9120/51/5/054002

Digital Object Identifier (DOI):
10.1088/0031-9120/51/5/054002

Published In:
Physics Education

Bringing the magic of light to remote areas where resources are scarce: Beautiful demonstrations of interference patterns using laser pens and fibres

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Keywords: laser; diffraction; interference; double-slit experiment; surface waves; international development

Abstract:

The training of physics teachers in remote areas in the developing world require s dedicated trainers (who typically are volunteers), as well as robust logistics. The latter must include the supply of equipment for experiments in the classroom. This task is greatly aided by the use of cheap, safe and readily available consumer goods that do not require local power supplies. In this paper, a simple experiment using a laser pointer pen and samples of hair as well as wire and transparent thin fibre is presented, reproducing a variant of Thomas Youngs' famed double slit experiment. The spread of the interference pattern as it projects itself on a screen is sufficiently large to catch the interest of students, and its orientation being perpendicular to that of the hair is also strikingly counter-intuitive. The students are then encouraged to apply the simplified Fraunhofer equation to the various samples to find out the width of their hair. Ideally, these samples would also include calibrating materials like fibres and wires of known diameters, the use of which should give confidence in the model by confirming that it can predict the sample diameter. A fruitful discussion supported by diagrams can also be conducted on the differences that coul d be expected between a straight edge and a rounded edge, the latter throwing an unexpected challenge to the initial model. However, the use of a transparent fibre also clearly illustrate the limitations of this model, a perception that is amplified by the particularly wide and bright interference pattern that it produces. This mismatch between the model and the real system should prompt the students to further refine their description of the physical system and the resulting model. Throughout the session, their reasoning may be helped by encouraging them to produce diagrams showing the path of optical rays.

1. Introduction

Thomas Young's original experiments on the diffraction and interference of light in the early years of the 19th century were decisive in proving the wave-like nature of light [1].

Generally, the concept is demonstrated in the classroom in a very similar manner to Young's original experiments, and usually the double slit experiment is used. Nowadays, cheap and widely available laser sources are increasingly used instead of lamps, with the advantage that their monochromatic light produces very clearly defined nodes in the fringes without the need for a filter [2]. However, little else has changed, and the screens and splitting devices are still pretty much specialist equipment that must be bought for the classroom.

Young also used a hair to a similar effect to that produced by the screen with double slit, this time the edges of the hair behaved like the emitting sources [1]. What we present here is a simpler demonstration of the same hair experiment, making use of the wide availability and very low cost of laser pointers. The focused nature of the laser beam neatly avoids the use of screens on the side. We also would like to point out the strong impression that it can produce on the observer. The brightness of the light means that the fringes appear as a dashed line that remains very visible at large distances (sometimes tens of centimetres) away from the centreline. Provided that the hair or fibre is fairly straight, this dashed line appears to be perpendicular to its direction, an observation which combined with the unexpected long length of the dashed line should impress the observer.

A similar demonstration was mentioned in a short note by Greenslade Jr. [3], who used one of his cat's whisker and a He-Ne laser. However, the note solely emphasized the effect that the tapering of the whisker has on the spacing of the fringe, rather than the overall visual effect or the potential for further extension and insight.

This experiment could be of particular interest in the classroom if resources are very limited, for example in rural areas of developing countries where even the electricity grid is typically weak or non-existent. In fact, the motivation and inspiration behind this paper came from the work done by volunteers from the Institute of Physics who train teachers in Malawi [4] as part of the IOP's *Physics for Development* programme [5]. A couple of dollars would pay for a battery-powered laser pointer, and local materials can be used to provide supporting structures. The same experiment can also be combined with others that use laser pointers and cheap materials (e.g. references [6]-[17]).

2. Materials and method

While the required equipment is not regarded as being particularly hazardous, laser radiation can nevertheless cause harm and a risk assessment must be conducted. School teachers should refer to CLEAPPS guidance in England, Wales and Northern Ireland [18], or SSERC guidance in Scotland [19]. The laser pointer must be of class 1 or 2 as defined in the IEC 60825-1 standard [20] (i.e. class I or IIa of the previous ANSI Z136.1 standard).

The laser is pointed straight at a matt vertical wall or screen at a distance L from the aperture, with the hair or wire of diameter d_o held at a short distance in front of the laser aperture (a few millimetres). If a clamp is too coarse in its grip or positioning, the hair may be secured in position with a more convenient implement, for example a washing line peg, itself held by the clamp. Any hair sample must first be visually inspected to ensure an approximately cylindrical shape, and it must be straight or pulled so. Duct-taping or otherwise fastening a ruler or measuring tape (preferably with a matt finish) on the screen is helpful for recording the result of the experiment, or alternatively graph paper may be used. Figure 1 illustrates this set-up.

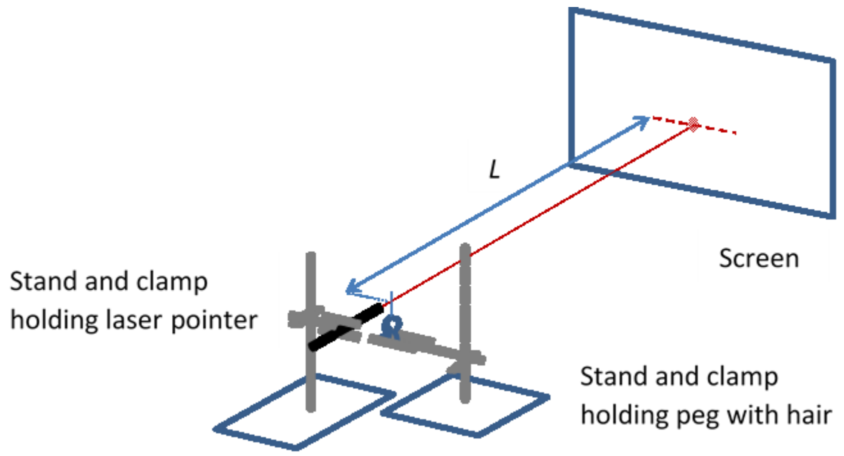

Figure 1: Example of experimental set-up.

Everyone must move behind the pointer before the laser is switched on.

Assuming $d_o << L$ (the 'far field' for the Fraunhofer's equation), Young's formula links d_o, L, the spacing D between consecutive minima of intensity in the diffraction fringe, and the wavelength λ of the incident light:

$$d_o = \lambda\, L / D \qquad \text{(Eqn. 1)}$$

In these experiments, we used a class 1 red laser pointer advertised as having a power output of 1mW and wavelength 650 nm (supplier not known).

The distance D in Eqn. 1 was obtained as the average value within a series of consecutive, well-defined dashes of light on the pattern on one side of the central spot. Assuming that λ is known, this estimate for D would be expected to be the dominant contribution to the uncertainty of d_o in Eqn. (1), since L can be determined within +/- 1mm over 1m, whereas the uncertainty on D (arising from the combined uncertainties on the positions of two minima) will be of the order of +/- 2mm over distances of about 50 mm, i.e. about one order of magnitude larger.

Since cheaply available laser pens come with limited technical information (and often no information regarding the identity of the manufacturer), it is recommended to calibrate the experiment with threads or wires of known diameters. This also provides a direct mean of assessing the accuracy of the method. Here we used tinned copper wire supplied by RS Components Ltd, 0.152 mm (SWG 38), and a monofilament nylon thread of 0.15 mm diameter supplied by HaberCraft Ltd. Ideally, the specified tolerance on the diameter, if any is available from the supplier, would also be referred to – though this is not strictly necessary for the purpose of this educational experiment.

3. Results

Unless specified otherwise, L was set at 2.000 m +/- 0.002 m in all the experiments.

3.1 Tinned copper wire

Figure 2 shows the pattern produced by the 0.152 mm tinned copper wire.

Wire breadth = Distance to wall x wavelength / distance between consecutive shaded area

= 2000 x 0.00065 / (50/6) = 0.156 mm

with an uncertainty of +/- 2 mm over 50 mm, i.e. +/- 4%, or +/- 0.006 mm.

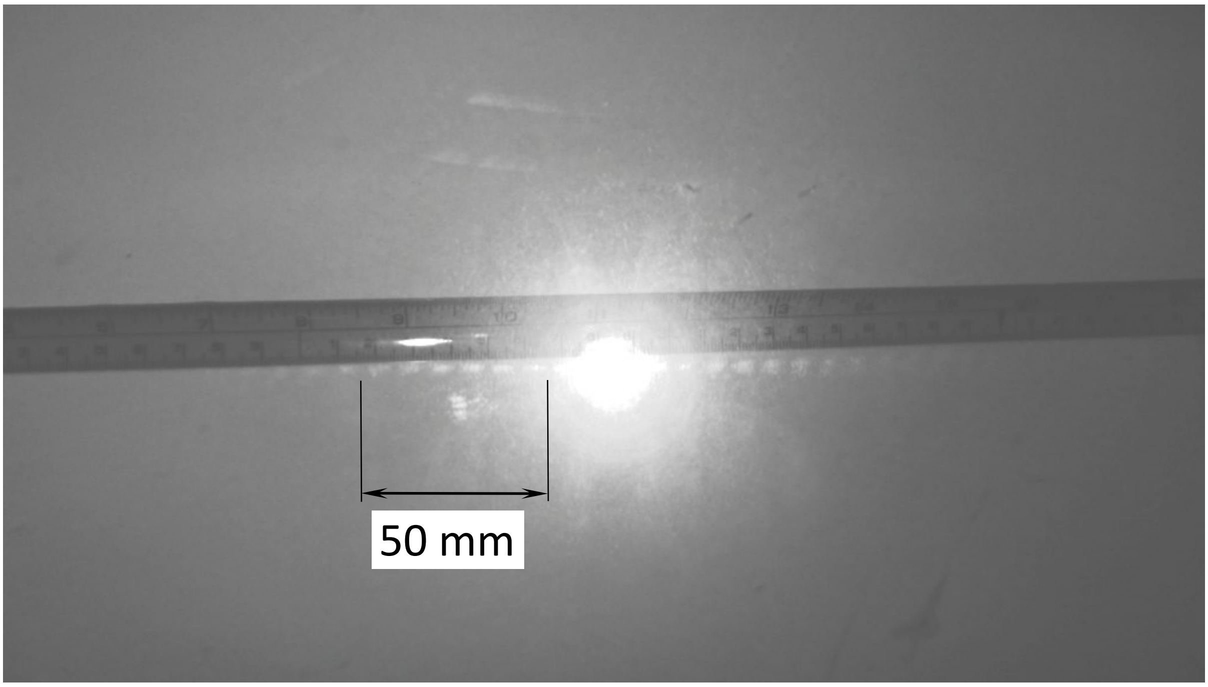

Figure 2: Pattern produced by tinned copper wire, 0.152 mm diameter (SWG 38), at L = 2.00 m.

3.2 Nylon monofilament

Figure 3 shows the pattern produced by the 0.150 mm nylon thread in the same conditions as for Figure 2. This time,

Fibre breadth = 2000 x 0.00065 / (52/6) = 0.150 mm +/- 0.006 mm.

However, this result should be treated with caution. Firstly, the pattern had a distinct appearance in that it seemed brighter overall and stretched over a distance several times longer that produced by either the wire or hair samples (Figure 4). In addition, beyond a handful of dashes away from the central spot the separation between dashes of light also appeared to be less bright (i.e. the intensity of minima varied), and individual dashes varied in brightness. Finally, the dashes of light appeared about twice as long at some distance from the central spot as they were nearer the spot: at 0.8 m, we could count 8 dashes spread over 130mm, i.e. a separation of 130/8 = 16.5 mm between minima, which when used as input for Eqn. 1 would give an erroneous value of 0.079 mm.

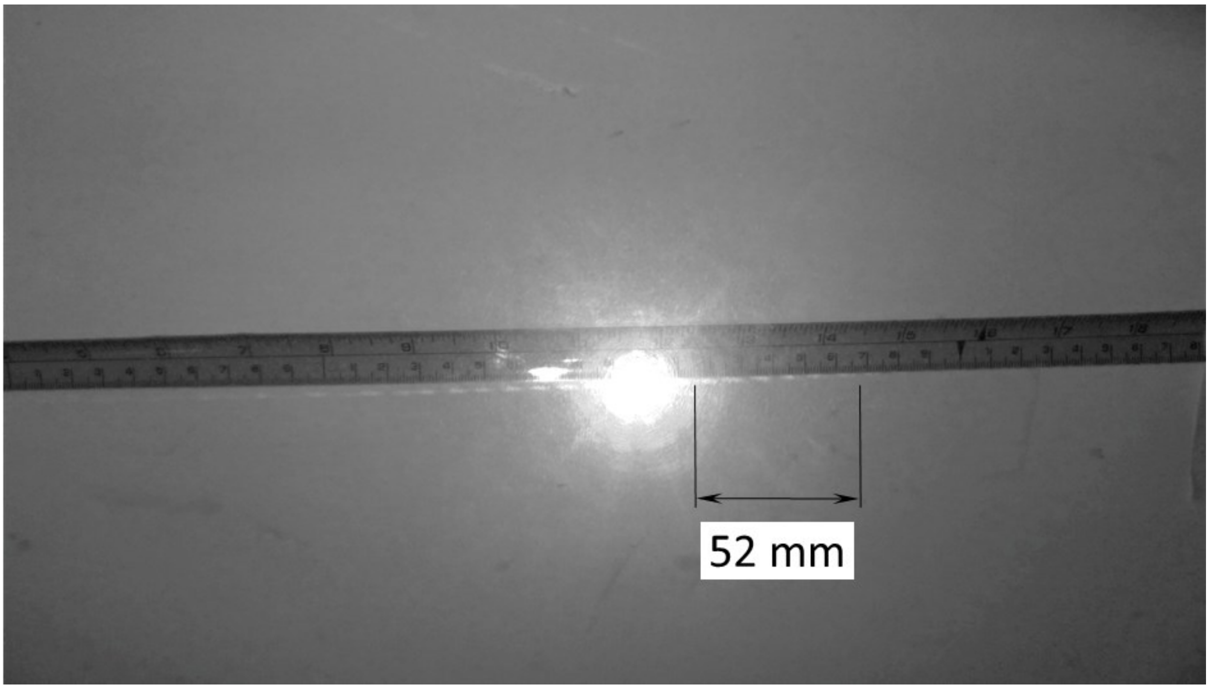

Figure 3: Pattern produced by monofilament nylon 0.15 mm diameter), at L = 2.00 m.

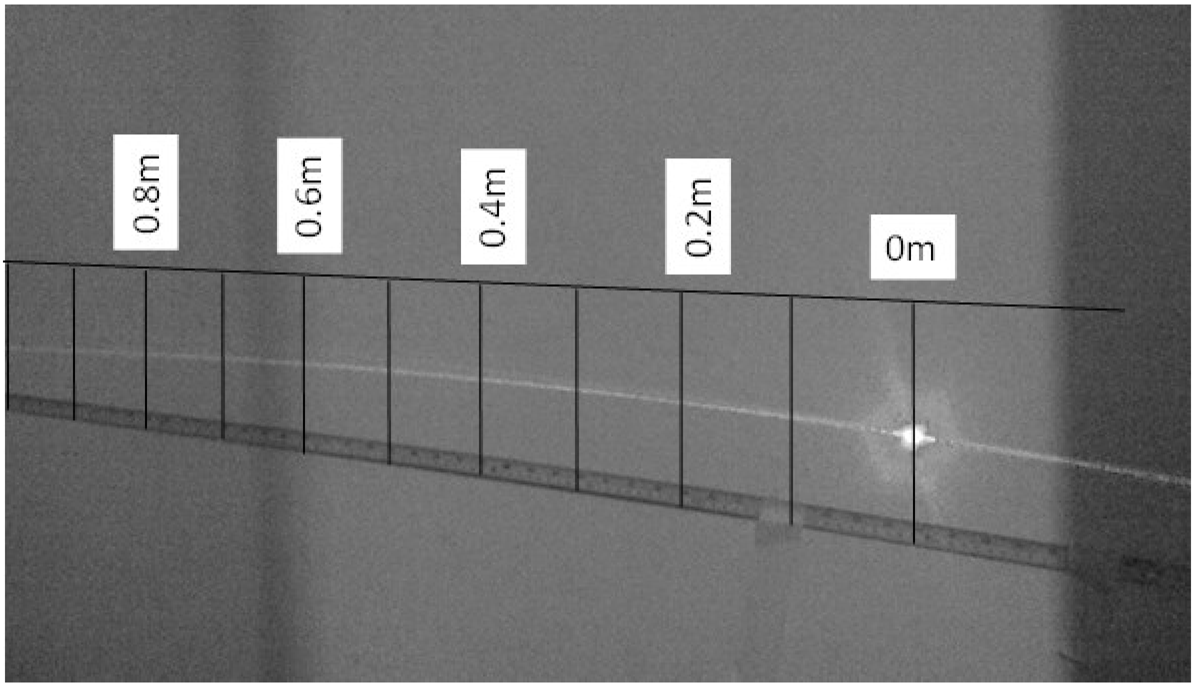

Figure 4: Same conditions as in figure 3, showing the extent of the pattern (> 1m on each side).

3.3 Hair

Figure 5 shows the pattern produced by a sample of human hair. This time L was reduced to 0.6 m +/- 0.002 m and the room was darkened. The greater contrast reduced the apparent width of the shaded gaps, allowing lower uncertainty in positioning them (+/- 0.5 mm for each)

Hair breadth = 600 x 0.00065 / (47/9) = 0.075 mm +/- 0.0015 mm.

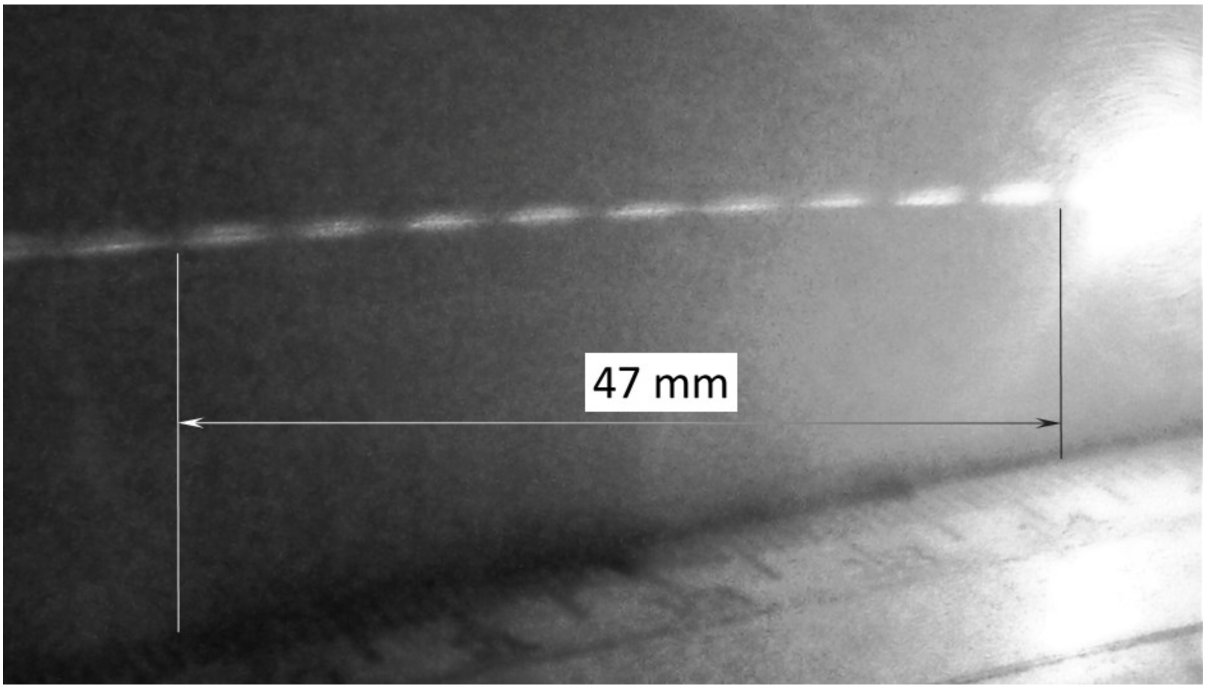

Figure 5: Pattern produced by a human hair, this time at L= 0.6 m in a darkened room. The picture is showing the left hand side of the pattern only.

4. Discussion

The following discussion aims at highlighting some issues with the theory and the method, to stimulate discussion in the classroom and the student's development.

4.1 Apparent success of the experiment

The experiment is very cheap and straightforward to set-up, and even with daylight in the classroom the pattern is easy to see. Calibrations experiments seem to confirm that accuracy is within a few % at most from the expected value of the diameter of the object under observation.

4.2 Conceptual issues arising from Eqn. 1

Typically, Equation 1 assumes that Babinet's principle applies in the far field, i.e. the hair, wire or other cylindrical body can be equivalently substituted by an aperture within a screen whose dimension and position matches that of a two dimensional projection of the body into the plane of observation [21]. However, students might query how the light can diffract from the edge of the shaded area of the cylinder without somehow crossing through some of the cylinder material, since the tangent at the surface is aligned with the direction of the incident ray. Solving the problem requires due consideration of the dielectric properties of the cylinder (at least on its surface), which can be done with Maxwell's equations as presented by Rayleigh nearly a century ago and by others

[22]. The corresponding physical interpretation involves surface waves of light that result from the coupling of the light with the excitation of dipoles at the surface of the cylinder. The waves propagate along the surface in an extension of Fermat's principle of "least time", and leave from behind to allow the rays to penetrate into the shadow of the object [23, 24].

A simple geometrical construction shown in Figure 6 can be used by students to estimate that it should be enough for the light to 'creep' over distances of a couple of wavelengths along the circumference of the cylinder before diffracting in order to account for the observed spread of the interference pattern behind the cylinder.

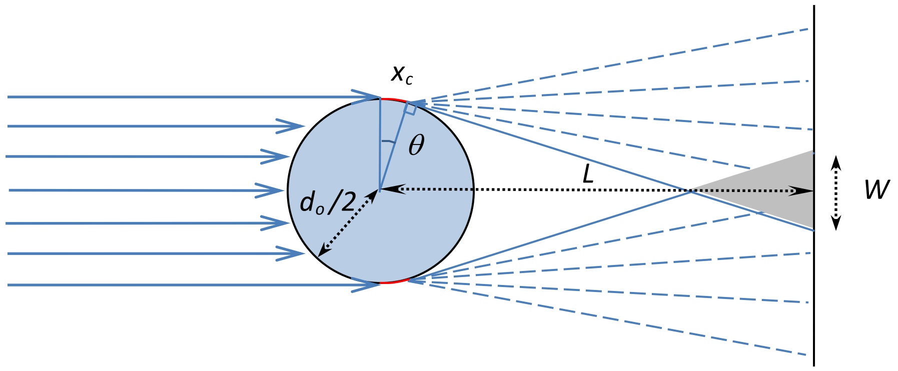

Figure 6: A cylinder of diameter d_o obstructs light at normal incidence (on the left hand side). The light at grazing incidence 'creeps' over a distance x_c along the circumference of the cylinder before diffracting in all directions. Only some of the diffracted rays that are going towards the right are shown here, in particular those tangent to the circumference which are shown as solid lines. The latter define the boundaries of the interference pattern, which is shown as a shaded triangle on the figure with a width W at a distance L from the cylinder. (NB: Dimensions are not to scale. In particular, the diameter of the hair has been exaggerated by 3 to 4 orders of magnitude with respect to L and W).

Defining x_c as the propagation length of the surface wave, and W the width of the interference pattern at distance L from the cylinder, we have the following relationships:

$$W + d_o = 2L \cdot \sin\theta \qquad \text{(Eqn. 2)}$$

and

$$x_c = \theta \cdot d_o / 2 \qquad \text{(Eqn. 3)}$$

Since θ is small and $d_o \ll W$, Eqn. 2 can be approximated as $W \approx 2L \cdot \theta$, which allows straightforward substitution of θ in Eqn. 3. Hence,

$$x_c \approx d_o \cdot W / 4L \qquad \text{(Eqn. 4)}$$

At L = 2m with hair we observed $W \approx 0.3$ m with $d_o \approx 0.08$ mm hence $x_c \approx 3$ μm. This represents about 4 to 5 wavelengths of the monochromatic light used in the experiment.

Likewise with wire, we would get $x_c \approx 6$ μm.

However, the overall width of the diffraction pattern for the nylon monofilament could not be explained with this model, since its value was of comparable order of magnitude to that of L as shown in Figure 4 – an observation which we are discussing in the next section.

4.3 Influence of materials

The strikingly brighter and more extended diffraction pattern produced by the nylon thread as compared with the other materials may be a great advantage in the classroom, but it comes with additional complexity in the interpretation. Nevertheless, this may be a great opportunity to stimulate students thinking with enquiry based learning.

Firstly, the students should be encouraged to describe the interference pattern to the same level of detail as was presented in section 3.2. When prompting them to suggest distinctive properties for the nylon thread that may account for the observations, they should remark that the nylon thread was transparent unlike the wire or the hair samples. Therefore, refraction and internal reflection could contribute to the diffraction pattern. In particular, the thread would be expected to behave like a cylindrical lens, focusing the beam behind the cylinder. These focused rays would then diverge and interfere with the diffracted rays at wide angles.

This type of mechanism was in fact proposed by Harris [25] for explaining the experimental results presented by Lundberg on the light scattering pattern produced by Nylon 6-6 fibres illuminated by a 632.8 nm wavelength He-Ne laser [26]. Figure 5 on Lundberg's paper showed the minima near the centre to vary in intensity, and the dashes away from the centre to have about twice the length just as we too observed. Allen-Booth and Eaton [27] also provided a detailed description of the underlying mechanisms when using changes to the fringe pattern when a nylon fibre was stretched as part of an elegant demonstration to estimate the Poisson's ratio of the material.

It may be worthwhile asking the students to interpret the results in a very approximate way, by asking them to modify Figure 6 to include the path of rays that get transmitted and focused by the transparent cylinder. In the shaded area on Figure 6 the refracted rays would diverge after the focal point, and they would now interfere with the diffracted rays on both sides of the cylinder, thus superimposing additional dashes of light on the expected pattern from interference of the diffracted rays. This would explain the varying intensity of the minima. Outside the shaded area, only one of the two diffracting edges could interfere with the refracted rays on any one side, thus producing a more regular pattern of dashes but with a distance between minima that may not be the same as what it is in the shaded area.

However, this explanation may not be sufficient on its own for explaining the difference in pattern between hair and nylon, since human hair is typically translucent. Typically, hair has a transmittance (defined as the ratio of light intensity that is transmitted through the hair to that which is incident) in the range 0.45 – 0.65 for the red part of the visible spectrum (625 nm was used in [28]); and a refractive index of about 1.55 over the visible spectrum [29]. By comparison, the nylon monofilament used here has a transmittance close to 1, and a refractive index of ca. 1.5 [30]. The two fibres must be different in other respects that impact on light transmission, reflection and diffraction. For example, the hair surface is not smooth at all, having instead a scaly appearance at sufficient magnification [31]. The nylon fibres by contrast are smooth and reflective, with Allen-Booth and Eaton [27] attempting to model the interference pattern at wide angles by combining the rays that are reflected at the surface with those that are refracted through the fibre.

4.4 Practical applications

Finally, it may be of interest asking students what practical applications they think these observations may have. One of them is quality control in the manufacture of wires or fibres [21, 25]. Another one might be party lights for dance floors. Beyond wires and fibres, diffraction (i.e. strictly speaking, interference) patterns are also of interest for the sizing and characterization of particulates in research and industry laboratories.

5. Conclusions:

The experiment described here is very cheap and straightforward to set up, and also of sufficient depth to prompt discussions that allow students to query further the physics behind the observations and the models that are used to attempt describing and predicting these observations. In particular, the comparison between the expected behaviour of straight and rounded edges, and the different patterns produced by distinct materials both provide insight into the assumptions behind the model and should stimulate the students thinking. This experiment can also be integrated with others that were described in the introduction as part of a more comprehensive introduction to optics.

Acknowledgments

The author wishes to thank all volunteers who lent their time and samples when he checked that the experiment worked on different types of hair. In addition, special thanks are owed to Dr. Olivia Roche for providing the initial suggestion of writing this paper and some feedback during preparation. As an experienced trainer of teachers in Malawi on the IOP's Physics for Development programme, her input was essential.

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